THE PLANETARY WAVES OF OZONE AND TEMPERATURE AND THEIR WAVE TRANSPORT DURING THE MIDDLE FEBRUARY 1981 WARMING

By

Pi-Huan Wang[1]

Science and Technology Corporation

Hampton, Virginia 23666

M. P. McCormick and W. P. Chu

Atmospheric Sciences Division

NASA-Langley Research Center

Hampton, Virginia 23665

(NASA-CR-185104) THE PLANETARY WAVES OF OZONE AND TEMPERATURE AND THEIR WAVE TRANSPORT DURING THE MIDDLE FEBRUARY, 1981 WARMING (Science and Technology Corp.) 46 p

N89-71134

Unclas

00/90 0213165

---

[1]Formerly employed by Institute for Atmospheric Optics and Remote Sensing (IFAORS), Hampton, Virginia 23666.

ABSTRACT

The planetary waves of stratospheric ozone and temperature and their meridional wave transport near 52°N during the middle February 1981 warming have been examined in detail by using ozone profiles derived from the Stratospheric Aerosol and Gas Experiment (SAGE) and associated meteorological information. The computed results show clearly large temperature wavenumber 1 developments in the upper stratosphere centered at an altitude of 44 km, and also in the lower stratosphere with a peak at about 22 km. The maximum intensities, about 12°C and 10°C in the upper and lower stratospheres, respectively, occurred on February 15, 1981. In comparison, the corresponding wavenumber 2 component was much less intense, especially in the upper stratosphere, but its activities in the lower stratosphere centered at 22 km were clearly visible. During almost the entire data period of this study, wavenumber 2 activity was declining. The results of the corresponding ozone mixing ratio wave exhibit a distinct development of wavenumber 1 in the upper stratosphere centered at 44 km, with the peak intensity occurring also on February 15, 1981. In the lower stratosphere, the ozone wavenumber 1 activity was much less intense and remained rather steady during the entire period of this middle February warming. Similar behavior was found for the wavenumber 2 ozone mixing ratios. With respect to ozone eddy transports, the results show a layer with poleward transport between altitudes of approximately 30 km to 40 km. This transport was found to be declining during the middle February 1981 warming. Above 40 km, ozone was found to be transported equatorward with the peak intensity occurring on February 15 at an altitude of 44 km. The results also indicate that this ozone transport can be accounted for largely

by the wavenumber 1 activity. In the case of eddy temperature transport, the results show large poleward fluxes above about 30 km. A peak of the fluxes took place on February 14, 1981, at an altitude of 44 km. Like the case of the ozone transport, the wavenumber 1 component was found to account largely for the temperature transport. In addition, a comparison of the calculated results of this wavenumber 1 dominant middle February 1981 warming with those of the late February 1979 warming, which involves disturbances with an outstanding wavenumber 2 component, is discussed.

1. INTRODUCTION

Due to its role in protecting the surface environment from harmful ultraviolet radiation and in affecting the earth's climate, the behavior of the atmospheric ozone layer has been a subject of extensive investigation (NASA, 1979; Dütsch, 1981; WMO, 1981). It has been recognized that the ozone distribution is maintained by a complex interaction of photochemical, dynamical, and radiational processes (e.g., Dütsch, 1971; Cunnold et al., 1980; Hartmann and Garcia, 1979; Garcia and Hartmann, 1980; Hartmann, 1981). The first theoretical photochemical model that explained the existence of the stratospheric ozone was developed by Chapman (1930); the so-called Chapman reactions (see, e.g., Craig, 1965). Later in the 1940s, it was shown that the observed ozone distribution in the lower stratosphere could only be understood if it was influenced by meridional ozone transport during the winter season (e.g., Craig, 1950).

Perhaps one of the most interesting features of atmospheric ozone is the northern spring maximum in the annual variation of total ozone occurring at high latitudes in the northern hemisphere. It was suggested that ozone transport, due to large-scale quasi-horizontal eddies, is responsible for this spring ozone buildup (Prabhakara, 1963; Newell, 1964; Craig, 1965; Dütsch, 1969, Cunnold et al., 1980; Holton, 1980a). There is no doubt that this spring total ozone buildup is closely associated with the development of stratospheric warmings. Both the spring total ozone maximum and stratospheric warmings are intimately related to the event of amplifying stratospheric planetary waves (see e.g., Holton 1980b). The amplification of those large planetary waves during the winter season is primarily the manifestation of the response of the stratosphere to meteorological disturbances in the troposphere. The planetary scale topography (Schoeberl and Strobel, 1980), and the thermal forcing due to land-sea heating (Dickinson, 1980), are believed to be sufficient to produce large-scale atmospheric disturbances.

In a sense, observation of the development of large-scale stratospheric ozone and temperature waves during the winter at high latitudes provide a unique opportunity for comparison with theoretical model prediction to assess current understanding of the behavior of stratospheric ozone. The development of this large-scale wave as a response of the stratosphere to tropospheric disturbances and also the transport effects of these waves have been investigated using theoretical models (Hartmann and Garcia, 1979; Garcia and Hartmann, 1980; Kawahira, 1982; Kurzeja et al., 1984; Rood and Schoeberl, 1983a,b). Meanwhile, studies based on satellite observations are becoming available (Barnett et al., 1975; Gille et al., 1980; Nagatani and Miller, 1984; Wu et al., 1985).

In addition, ozone data based on the Stratospheric Aerosol and Gas Experiment (SAGE) have been used recently in conjunction with the associated meteorological information to study the behavior of planetary waves of ozone and temperature and their wave transports during the late February 1979 stratospheric warming (Wang et al., 1983, hereafter referred to as WMC). Even though the analysis did not derive the detailed ozone budgets due to insufficient data, the results in WMC show many interesting features. Specifically, the ozone and temperature waves are shown to be in phase in the lower stratosphere (below ~25 km), out of phase in the upper stratosphere (above ~38 km), with a transition region in between. In the upper stratosphere, an intense equatorward eddy ozone transport was shown to be accompanied by a poleward eddy heat transport during this late February 1979 warming. The analysis in WMC (which is based on a single case study) also shows a rapid increase in ozone column density above 10 km over the data period analyzed. This increase was found to be primarily a response to the change of zonal mean ozone number density in the lower stratosphere. Since there is considerable variability in the manifestation of the warming events and amplifying planetary waves from year to year (Schoeberl, 1978; Labitzke, 1981; Labitzke and Goretzki, 1982), results from observations of different warming events are highly desirable.

The purpose of this study is twofold. First, the behavior of planetary waves of ozone and temperature and their wave transports during the middle February 1981 stratospheric warming will be studied in detail by utilizing the SAGE ozone measurements and associated meteorological data. Second, the analyzed results of this middle February 1981 warming will be compared with those of the late February 1979 warming described in WMC (1983). As will be shown, these two warming events correspond to two quite different stratospheric circulations at high latitudes. A comparison of the behavior of ozone and temperature waves between those two events may enhance our understanding of their behavior during warming events.

2. DATA AND APPROACH

Similar to WMC (1983), the results of SAGE ozone measurements and the associated meteorological information provided by NOAA's National Meteorological Center are used in this analysis of the mid-February 1981 warming event. In WMC, we have described the general characteristics of SAGE ozone and meteorological data sets relevant to the planetary wave studies. In this study, we will mention only specific aspects of these observations which are important to our analysis.

The SAGE instrument was carried aboard the AEM 2 satellite with a 55° orbit inclination and an orbital period of 96.8 min. The instrument utilized the solar occultation technique to measure the attenuation of solar intensity through the earth's atmosphere during spacecraft sunrise and sunset at wavelengths centered at 0.385, 0.45, 0.60, and 1.0 μm. The ozone concentration profiles were deduced from the measurements in the 0.60 μm channel centered at the peak of the Chappuis ozone absorption band (Chu and McCormick, 1979). As a result of the orbital characteristics, the successive SAGE sunrise/sunset measurements were separated by a 24° shift in longitude and a slight shift in latitude of about 0.2 - 0.3° at the latitudes of interest for this study (see table). Both sunrise and sunset measurements covered a latitude belt from 79°S-79°N (depending on the season), shifting from one extreme latitude to the other in about one and a half months, providing about 15 sunrise and 15 sunset measurements per day. Since the latitudinal shift was a minimum at the highest latitudes, the SAGE daily measurement locations were located along a nearly constant latitude circle at high latitudes. This measurement feature enables us to derive the planetary waves of ozone and temperature as well as their fluxes on a daily basis. Additional details of the SAGE observations can be found in McCormick et al. (1979).

It should be noted that about 5 months after the SAGE instrument was launched, the AEM 2 satellite power system developed problems. As a result, there were no sunrise measurements available after July 1979. The entire SAGE observation period covers 34 months from February 1979 to November 1981 (Fig. 1). For the purpose of examining the behavior of winter planetary waves, it is desirable to use data obtained at high latitudes where the waves are most active. As shown in Fig. 1, the SAGE measurement locations reached the highest northern latitudes on two occasions centered around January 1 and March 6 during the winter 1979-1980. Unfortunately, the highest latitude of the SAGE measurements around January 1, 1980, is about 46°N. As for the measurements near March 6, 1980, the highest latitude reached was 58°N, but data gaps were found in the retrieved profiles for this period. For these reasons, it was decided to examine the case of the winter 1980-1981 instead. During this winter, there were 10 consecutive daily SAGE ozone profiles from February 12 to 21, 1981, available for the analysis. The peak latitude near 54°N occurred on February 17, 1981. The table indicates the average latitude and the number of profiles of the SAGE daily measurements for these 10 days. The overall averaged latitude for this 10-day period is about 52°N which is only slightly lower than the February 1979 case discussed in WMC (1983). It is important to note that this 10-day period covered approximately the second half of the major midwinter warming which occurred in February 1981 as reported by Labitzke (1982).

In this analysis, the method for deriving the planetary waves of ozone and temperature and their fluxes using SAGE ozone and meteorological data sets is essentially the same as that described in WMC (1983). For this reason, we will not repeat the discussion here. Since one of the purposes of this study is to compare the ozone and temperature waves and their eddy transports between the late February 1979 and the middle February 1981 warmings, a general description on the synoptical meteorological aspects of the northern high latitude stratosphere during these warming periods is included in the analysis. These data will help to illustrate some features of the atmospheric circulation and thermal structure which are not obvious from an examination entirely in terms of their harmonic components. As will be seen in the next section, there are considerable differences in the stratospheric circulation pattern between these two warming events.

3. RESULTS AND DISCUSSION

In this section, we first show the development of the arctic circulation pattern for the middle February 1981 warming. For comparison, a description of the late February 1979 warming is included. The results of harmonic analyses of the ozone mixing ratio, temperature, and eddy meridional velocity are given in the second part of this section, followed by a description of the horizontal meridional ozone and temperature transports by planetary waves. In the last part of this section, the phase relationship between ozone mixing ratio, temperature, and eddy meridional velocity is examined.

a. Synoptical meteorology of the high latitude stratosphere for the middle February 1981 warming

Some aspects of the warming event of 1980-1981 have been discussed by Labitzke and Goretzki (1982). It began with the development of an Aleutian anticyclone which indicated the amplification of a wavenumber 1 disturbance in November 1980--the so-called Canadian Warming. In December 1980, the wave activities were generally mild and the monthly mean 30-mb North Pole temperature was -82°C--the coldest temperature since the winter 1958-1959. This situation extended to the middle of January 1981. During this period, the high latitude northern hemisphere was characterized by the development of an intense quasi-circular polar vortex as shown in the 30 mb upper air map on January 14, 1981 (Fig. 2a). Thereafter, this polar vortex was disturbed by amplifying planetary waves, mainly wavenumber 1 (Fig. 2b). By middle February, the high latitude zonal mean thermal structure showed a reversal of the latitudinal temperature gradient, indicating the occurrence of a major midwinter warming. According to Labitzke and Goretzki (1982), the monthly mean 30-mb North Pole temperature had increased from -82°C in December 1980 to -56°C in February 1981. Figure 2c shows the 30-mb upper air map on February 15, 1981, in which the remainder of the wavenumber 1 disturbance is still clearly evident. It is interesting to note that the wavenumber 1 height disturbance had shifted its phase by an amount close to 180° from January 25 to February 15. Note also that the cold center, which was located near the North Pole just before the development of planetary wave disturbances on January 14, 1981 (Fig. 2a), had moved to ~60°N latitude west of Canada by February 15, 1981. At the same time, warmer air masses had appeared in the polar region (Fig. 2c).

In the second half of February, the activity of planetary wave disturbances became much weaker and the polar vortex began to regain some of its strength (Fig. 2d). This stage corresponds to a period of the so-called "late winter cooling" (Labitzke and Goretzki, 1982). Later, there was a further development of wavenumber 1 disturbance which reached its peak intensity on about March 3, 1981. Thereafter, the arctic stratosphere was gradually replaced by the summer circulation system. It is interesting to note that Labitzke (1982) had shown that this wavenumber 1 dominated winter disturbance took place during the westerly phase of the equatorial quasi biennial oscillation (QBO) (at 50 mb), and not on the easterly phase as most wavenumber 1 developments show. She further indicated that only wavenumber 1 winter events which occurred near sunspot maxima exhibit this unusual feature. For comparison purposes, it is essential to this investigation to also describe the circulation which occurred in the polar region during the late February 1979 warming.

The synoptic aspects of the circulation of the winter 1978-1979 have been discussed by Noxon et al. (1979) and Syed and Harrison (1981) in their studies on the behavior of NO_2 abundance during the warming of January-February 1979. The behavior of planetary wave disturbances of the temperature and height fields of this winter also have been investigated in detail by Quiroz (1979) and Labitzke (1981). Before January 15, 1979, the polar stratospheric circulation system showed only mild fluctuations in these fields except for a few days around December 8, 1978. During these days, an Aleutian anticyclone developed indicating an amplification of height wavenumber 1. In the period beginning on January 15 to early March 1979, the northern polar stratospheric circulation system went through several interesting changes. First, there was the formation of an unusually strong Aleutian anticyclone which led to the amplification of wavenumber 1 disturbance at 30 mb with the peak intensity occurring on about January 26. Second, about the same day, the stratosphere showed the first reversal of the meridional gradient of mean stratospheric temperature. Thereafter, this anticyclonic system weakened and the disturbed polar vortex tended to regain its strength with its center moving back toward the pole.

Figure 3a shows the 30-mb arctic upper air map for February 9, 1979. This polar vortex became well established again by about February 12. Beginning that day, the vortex exhibited an elongation of its circulation pattern approximately along the east-west axis, with the appearance of two low pressure systems (Fig. 3b). Meanwhile, two high pressure systems developed on each side of the elongated polar vortex (Fig. 3b), indicating an amplification of wavenumber 2. This development in the arctic stratosphere culminated in the splitting of the polar vortex (Fig. 3c) and the reversals of the zonal mean arctic flow, as well as the meridional gradient of mean stratospheric temperature--a major final warming (Quiroz, 1979). By the end of February, these wavenumber 2 dominated disturbances began to decay. In the following month, there were only mild fluctuations of the height field in the form of wavenumber 1. During the month of April 1979, the flow in the arctic winter stratosphere was gradually replaced by the summer circulation system.

From the above discussion, it is clear that the development of the arctic winter disturbances in the two winters 1978-1979 and 1980-1981 are rather different. In the latter case, the arctic disturbances involved primarily wavenumber 1 fluctuations during the entire winter season. In the former case, on the other hand, the polar stratosphere showed disturbances involving both wavenumber 1 and 2 with each dominating during different periods. It should also be mentioned that in WMC (1983), the period of the data set analyzed only covered the peak of the wavenumber 2 development. The data set used in this analysis, however, covers essentially the second half of the major midwinter warming, the decaying stage of a strong wavenumber 1 disturbance.

b. Evolution of planetary waves

Figures 4a - 4c show the evolution of the temperature wavenumbers 1 and 2 disturbances and also the zonally averaged temperature during the mid-February 1981 stratospheric warming from February 12 to 21, 1981, respectively. In the case of the wavenumber 1 evolution (Fig. 4a), the stratosphere exhibits three distinct layers that are centered approximately at 22 km, 32 km, and 44 km, respectively. In the middle layer, a mild decrease in the wave amplitude is shown. The behavior of the waves in the lower and upper layers is very similar, showing an intensification in the first 4 days and a rather steady decay afterwards. The maxima of the wave amplitudes, approximately 12°C and 10°C in the upper and lower layers, respectively, appeared on February 15. The calculated amplitudes for wavenumber 2 temperature show generally a mild decay of the wave in the altitude region from 10 km to 50 km throughout the entire data period of this analysis (Fig. 4b). From Figs. 4a and 4b, it is clear that the temperature disturbances in this mid-February warming are dominated by wavenumber 1 activities. In the case of the zonal mean component (Fig. 4c), no significant variation is shown during this 10-day data period. However, a 2°C increase in the mean temperature is noticeable between 28 km and 38 km in the period from the 5th day to the 10th day.

In comparison with the case in WMC (1983), wavenumber 2 and mean temperature disturbances for this mid-February warming are smaller in magnitude. Wavenumber 1, however, is more intense overall, except in regions above ~38 km where they are comparable in magnitude.

The derived amplitude of the first two harmonic components of the eddy meridional velocity are shown in Figs. 5a and 5b, respectively. Wavenumber 1 shows an intensification from day 1 to day 3 above approximately 20 km (Fig. 5a). A peak value of 16.5 m/sec appeared on day 3 at about 37 km. Thereafter, the wave decayed. Below about 20 km, the wave amplitudes are relatively small (Fig. 5a). In Fig. 5b, the result of wavenumber 2 shows a decay of the wave throughout the data period of this study between 10 km and

50 km. The strength of the wavenumber 1 disturbance (Fig. 5a) is about 1.5 times that observed in WMC (1983), while the wavenumber 2 strength of the disturbance is only about half.

The first two harmonic components of the ozone mixing ratio are given in Figs. 6a and 6b. The noticeable features of the first component (Fig. 6a) are the appearance of a maximum of the mixing ratio at 44 km about February 15, 1981. The variation of ozone mixing ratio in a layer between 40 and 50 km seems to be associated with that of the temperature wavenumber 1 (Fig. 4a). Below about 40 km (Fig. 6a), a relatively steady-state condition is observed. In the case of ozone wavenumber 2 (Fig. 6b), the amplitude is only about half that of wavenumber 1. Figure 6b also shows that most of wavenumber 2 activities were in the upper stratosphere above about 30 km. Below 30 km, wavenumber 2 is relatively weak. The evolution of zonal mean ozone mixing ratio is given in Fig. 6c. Below about 30 km (Fig. 6c), little change is observed in the mean ozone mixing ratio during the data period of this study. In the layer between 30 km and 42 km, there is a slow increase in the ratio in the latter half of the period. Above 42 km, there is a noticeable decrease in the ozone mixing ratio in the entire data period of this study.

In comparison, the data shown in Figs. 6a and 6c are, in many respects, similar to those shown in WMC (1983, Fig. 6). In both cases, ozone wavenumber 1 disturbances are observed to be more intense in the upper stratosphere component. Slight increases are also observed in the zonal mean ozone mixing ratio in the lower stratosphere below 30 km. Particularly noteworthy is the fact that ozone wavenumber 1 disturbances in the upper stratosphere are clearly correlated to that of temperature wavenumber 1 in both warmings. This correlation between temperature and ozone wavenumber 2 amplitudes, however, is less clear in the analysis of these two warmings.

In order to examine the changes in the columnar ozone above 10 km during the mid-February 1981 stratospheric warming, the evolution of zonal mean ozone number density in this event is also derived based on the SAGE ozone data set. From Fig. 7a, which shows the computed results, it is evident that there is an increase in ozone concentration in the lower stratosphere centered at altitude 20 km. Above 24 km (Fig. 7a) no apparent changes in the mean number density are observed. It is interesting to note that the behavior of zonal mean ozone density in this mid-February 1981 warming is very similar to the late February 1979 event (WMC, 1983). The associated time variation in the ozone columnar density, given in Fig. 7b, exhibits a monotonical increase in value beginning on the 3rd day. This increase in ozone columnar abundance is primarily a response to the increase in the ozone concentration in the lower stratosphere as illustrated in Fig. 7a. A similar situation was also found in the late February 1979 stratospheric warming event (WMC, 1983). In comparing the ozone columnar density of this analysis with that described in WMC (1983), it is found that the overall values in the late February 1979 event are generally greater than those occurring in this mid-February 1981 warming.

c. <u>Horizontal ozone and temperature transports by planetary waves</u>

The computed eddy ozone transports associated with the first two wave components in the mid-February 1981 warming are displayed in Figs. 8a and 8b. The remarkable features of the wavenumber 1 transport (Fig. 8a) are the clearly defined altitude regions for the poleward and the equatorward ozone transports throughout the entire data period of this analysis. Above 40 km, a distinct layer of equatorward eddy ozone transport is observed (Fig. 8a), with a maximum value of 4.5 ppmv ms^{-1} occurring on February 14, 1981, at 44 km. Below about 28 km, an equatorward transport is also observed (Fig. 8a), but it is much weaker than the one above 40 km. In the layer between 28 and 40 km, the eddy ozone transport is mainly toward the North Pole. In this region, a slight increase in the transport is observed during the first 4 days, which decayed thereafter. A maximum poleward transport of 0.3 ppmv ms^{-1} appeared at 36 km on the same day (February 15, 1981) that the equatorward transport reached its peak value in the upper stratosphere.

An analysis of the ozone transport associated with wavenumber 2 indicates a poleward transport below 40 km and equatorward transport above 40 km in the first 2 to 3 days (Fig. 8b). Later, the equatorward transport system in the upper stratosphere is observed to increase slightly, reaching a peak value of 3 ppmv ms^{-1} at 46 km on February 15, 1981. On February 14, 1984 (Fig. 8b), a change in transport direction is observed within the layer between approximately 24 km and 38 km from poleward to equatorward. After February 15, the wavenumber 2 eddy ozone transport in the entire layer is observed to decay. From Figs. 8a and 8b, it is evident that the wavenumber 2 eddy ozone transports are generally weaker than wavenumber 1 in this particular warming. The sum of the eddy ozone transport due to the first three wave components is given in Fig. 8c. Since the transport due to wavenumber 1 is relatively strong, the transport shown in Fig. 8c exhibits features similar to those shown in Fig. 8a. By comparing Fig. 8c with the corresponding results presented in WMC (1983), one will notice that they exhibit generally similar features. In both cases, the ozone mixing ratio transport exhibit three distinct layers, namely, two equatorward transport layers (one in the upper stratosphere and one in the lower stratosphere) and a poleward transport layer in the middle stratosphere. There are, however, slight differences in the vertical extension and the center altitude of these layers for the two warming cases.

Since eddy ozone mass transport is directly related to changes in total ozone amount, the contributions of the first two wave components to this transport during the mid-February 1981 warming are analyzed (Figs. 9a and 9b). Below about 26 km, the development of an intense equatorward wavenumber 1 transport is observed (Fig. 9a). This transport reached a peak intensity of 2.7 x 10^{12} molecules $cm^{-3}ms^{-1}$ at 16 km about February 17, 1981. Above 26 km, the wavenumber 1 transport is relatively weaker than below. Nevertheless, a layer of poleward mass transport between 26 km and 38 km and also a layer of equatorward transport above 38 km are noticeable (Fig. 9a). The calculated results of wavenumber 2 ozone mass transport indicate a contribution that is generally much smaller than that of wavenumber 1 except in regions below 22 km during the first 2 to 3 days (Fig. 9b). In these regions, poleward eddy transport is observed during those days. The sum of the first three components of eddy ozone mass transports is displayed in Fig. 9. It is obvious that an intense equatorward transport developed below approximately 26 km. This development seems to be associated with the decaying of a poleward eddy ozone mass transport in the layer between 26 km and 40 km as revealed from the first 3 days of this data period. Although this poleward transport became rather weak by the 3rd day, a thin layer of poleward transport centered at altitude 34 km is still noticeable in the remainder of the data period. From Fig. 9, it is clear that the wavenumber 1 component plays a dominant role in the eddy ozone mass transport in this mid-February 1981 warming. As indicated in Fig. 9c, the peak of the equatorward transport occurred around February 16, 1981, at ~16 km. The vertical integrated mass flux of ozone (10-30 km altitude) on this day is found to be $(3.2 \pm 0.08) \times 10^{20}$ molecules cm^{-2} cms^{-1} to the south.

In WMC (1983), the ozone and temperature eddy transports in the upper stratosphere (above 35 km) were shown acting in opposite directions in both wavenumber 1 and 2 components. Of particular interest, both the wavenumber 1 ozone and temperature eddy transports show a change in their direction on about the same day. To see whether such a feature exists in the middle February 1981 warming, the eddy transports of temperature have been calculated. The results are shown in Fig. 10. The most distinct feature of the temperature wavenumber 1 transport (Fig. 10a) is the development of a poleward transport above about 30 km with the peak at about 44 km. This peak reached its maximum intensity (~67°K m/sec) on approximately February 14, and decreased steadily thereafter. Below about 30 km, only mild equatorward eddy heat transports are observed (Fig. 10a). In the case of wavenumber 2, a decrease of the poleward heat transport is generally observed throughout most of the altitude range of this study during the middle February 1981 warming (Fig. 10b). The net eddy heat transports is shown in Fig. 10c. It exhibits a rather similar time variation as that of wavenumber 1, with a distinct layer of poleward eddy heat transport above

30 km centered at about 40 km, particularly on February 14. It should be noted that the daily values of the temperature difference between 80°N and 50°N at 30 mb pressure level exhibit a temperature reversal on about February 14, 1980 (Labitzke, 1982). This activity occurred about the same time that the eddy heat transports began to change direction from poleward to equatorward. As mentioned earlier, the wavenumber 1 ozone transport during the period of the data set in this study shows the peak equatorward transport at an altitude of 44 km. In addition, this peak reached its maximum intensity also on February 14. Thus, the observed wavenumber 1 of ozone and temperature transports are negatively correlated during this mid-February 1981 warming. In the case of wavenumber 2, it is found that the behavior of ozone and temperature transports are showing similar negative correlation above 40 km. In particular, in this altitude region, they both changed transport direction sometime between February 20 and 21.

d. <u>Phase relationships between the eddy fields</u>

The phase relationship between ozone, temperature, and meridional velocity waves of wavenumber 1 component on February 13, 1981, is shown in Fig. 11a. The horizontal bars, as in WMC (1983), are the computed uncertainty of the calculated phase based on the given uncertainty of SAGE and meteorological data. It can be seen in Fig. 11a that the ozone and temperature waves are nearly out of phase above approximately 42 km, whereas below about 27 km, they are closely in phase. In the region between approximately 27 km and 42 km, a change from the in-phase relationship below 27 km to an out-of-phase one about 42 km takes place. As to the phase relationship between ozone and meridional waves, it is observed that they are generally out of phase below about 25 km and above approximately 43 km

(Fig. 11a). They become closely in phase at altitudes centered at 30 km. This phase relationship explains the vertical variation of the wavenumber 1 ozone transport which was observed on February 14, 1981 (Fig. 8a). The phase relationship between temperature and meridional waves can also be seen in Fig. 10a. In the region above 32 km, their phase difference is less than $\pi/2$ and is greater than $\pi/2$ in the region below. This feature explains the two distinct regions of different heat transport direction which were observed on the corresponding date (Fig. 10a). The phase relationship of wavenumber 2 components on February 13, 1981, is shown in Fig. 11b. The ozone and temperature waves are observed to be out of phase above 42 km. Below 38 km, they are generally in phase. A similar phase relationship also can be found to exist between ozone and meridional velocity waves. The wavenumber 2 component of the temperature and meridional velocity waves are observed to be closely in phase throughout the entire altitude range of this study on February 13, 1981. This phase relationship between temperature and meridional waves accounts for the poleward heat transport at all altitudes on this particular date. The phase relationship between ozone, temperature, and meridional velocity waves on February 17, 1981, are shown in Figs. 11c and 11d for wavenumber 1 and wavenumber 2, respectively. As can be seen, the phase relationships are generally similar to those on February 13 between the corresponding wave components.

The detailed time variation of the wavenumber 1 phase relationship over the period of the data set at altitudes 44 km and 26 km are shown in Figs. 12a and 12b, respectively. The former shows the typical phase relationship in the upper stratosphere and the latter depicts that in the lower stratosphere. It is evident that an out-of-phase relationship between ozone and temperature waves in the upper stratosphere and a nearly in-phase relationship in the lower stratosphere occurred throughout during the mid-February 1981 warming. Similar phase relationships can also be found for wavenumber 2 components (Fig. 12c and 12d). The evolutions of the phase of meridional velocity waves are also shown in Figs. 12a to 12d for comparison.

4. SUMMARY AND CONCLUSIONS

In this paper, the planetary waves of the ozone mixing ratio, temperature, and meridional velocity near 52°N during the middle February 1981 stratospheric warming have been analyzed by utilizing SAGE ozone data and associated meteorological information. In addition, the eddy ozone and temperature fluxes during this warming were also examined.

The results show clearly large temperature wavenumber 1 developments in the upper stratosphere centered at an altitude of about 44 km and also in the lower stratosphere with a peak at about 22 km. The maximum intensities of approximately 12°C and 10°C in the upper and lower stratospheres, respectively, occurred on February 15, 1981. Comparatively, the corresponding wavenumber 2 component is much weaker in intensity, especially in the upper stratosphere. Nevertheless, the wavenumber 2 activities in the lower stratosphere, centered at 22 km, are clearly visible in the computed results and were observed to decrease during almost the entire data period of this study. With respect to the meridional velocity waves, the peak intensity of the wavenumber 1 component occurred at an altitude of about 37 km on February 14, 1981. The corresponding wavenumber 2 component exhibited an overall decline of the wave amplitude during this middle February 1981 warming. The analysis of the ozone mixing ratio wave during this period exhibits a distinct development of wavenumber 1 in the upper stratosphere centered at 44 km, with the peak intensity occurring on February 15, 1981. In the lower stratosphere, the ozone wavenumber 1 was much less active and remained rather steady throughout the entire period of this middle February warming. This also seems to be the case for the wavenumber 2 ozone mixing ratio waves. With respect to the ozone eddy transports, the results show a layer with poleward transport between approximately 30 km and 40 km. This transport was found to be decreasing during this warming period. Above 40 km, ozone was being transported equatorward with the peak intensity occurring on February 15 at 44 km. The results also indicate that the wavenumber 1 activity is the dominant component in this ozone transport. In the case of eddy temperature transport, the results show large poleward fluxes above about 30 km. The peak of the fluxes occurs on February 14, 1981, at 44 km. Similar to the case of ozone transport, the wavenumber 1 component is found to be primarily responsible for the temperature transport.

The results of this warming have also been compared with those of the late February 1979 warming. For completeness, the synoptic aspects of the large scale disturbances during the winter of 1980-1981 were discussed and similar discussions for the winter of 1978-1979 were included for comparative purposes. It is interesting to note that in contrast to the late February 1979 warming which involves disturbances with a wavenumber 2 component, this middle February 1979 warming is associated primarily with large amplifying wavenumber 1 disturbances (Figs. 2c and 3c). Despite the distinct difference in the planetary wave activities between these two warming events, many common features are clearly evident. First of all, the results show that the development of the ozone wavenumber 1 component in the upper stratosphere was closely associated with that of corresponding temperature waves. More specifically, they are negatively correlated. This feature is also noticeable in the case of the wavenumber 2 component, although it is not as distinct as is wavenumber 1. Furthermore, in both warmings, there was a rapid increase in the zonally averaged ozone column abundance. This increase was shown to be a response to the increases of the zonal mean ozone number density in the lower stratosphere centered at an altitude of about 20 km. With respect to the ozone mixing ratio transports associated with the waves, the results generally show the equatorward transport in the upper stratosphere and poleward transport in the middle stratosphere. In the lower stratosphere, the transport is much less intense. The equatorward ozone transport in the upper stratosphere is found to be accompanied by poleward heat transport during both warming events. As to the phase relationship between ozone and temperature waves, the computed results of this warming event also show three distinct layers, i.e., an out-of-phase relationship in the upper stratosphere and an in-phase relationship in the lower stratosphere, with a transition layer in between.

Finally, in contrast to the warming case studied by WMC (1983), which involves wavenumber 2 activity, this analysis was devoted to a warming dominated by wavenumber 1 development. Although the data period covers only 10 days, it includes the second half of the major midwinter warming according to Labitzke and Goretzki (1982). Furthermore, like the analysis of WMC (1983), the results of this investigation can provide useful information for modeling winter circulation in the northern high latitude stratosphere and for simulating planetary wave development and its transport effects.

5. ACKNOWLEDGMENTS

We would like to express our appreciation to L. R. McMaster and the SAGE data processing team for their helpful comments during the course of this study. One of us (Pi-Huan Wang) was supported by NASA Contract NAS1-17032.

6. REFERENCES

Barnett, J. J., J. T. Houghton, and J. A. Pyle, 1975: The temperature dependence of the ozone concentration near the stratopause. Quart. J. Roy. Meteor. Soc. 101, 245-257.

Chapman, S., 1930: A theory of upper atmospheric ozone. Phil. Mag. 10, 345-352.

Chu, W. P., and M. P. McCormick, 1979: Inversion of stratospheric aerosol and gaseous constituents from spacecraft solar extinction data in the 0.38-1.0 um wavelength region. Appl. Opt. 18, 1404-1413.

Craig, R. A., 1950: The observations and photochemistry of atmospheric ozone and their meteorological significance. In the Observations and Photochemistry of Atmospheric Ozone, Meteorol. Monogr. 1 (2), AMS, Boston, 50 pp.

Craig, R. A., 1965: The Upper Atmosphere and Physics, Academic Press, New York, 509 pp.

Cunnold, D. M., F. N. Alyea and R. G. Prinn, 1980: Preliminary calculations concerning the maintenance of the zonal mean ozone distribution in the northern hemisphere. Pure Appl. Geophys. 118, 284-306.

Dickinson, R. E., 1980: Theory and observation in Orographic Effects in Planetary Flows, WMO GARP Publ. No. 23, 51-84.

Dütsch, H. U., 1969: Atmospheric ozone and ultraviolet radiation. World Survey of Climatology, Vol. 4, Climate of the Free Atmosphere, D. F. Rex, Ed., Elsevier, 383-432.

Dütsch, H. U., 1971: Photochemistry of atmospheric ozone. Adv. Geophys. 15, 219-322.

Dütsch, H. U., 1981: Ozone research-Past--Present--Future. Bull. Amer. Meteor. Soc. 62, 213-217.

Garcia, R. R. and D. L. Hartmann, 1980: The role of planetary waves in the maintenance of the zonally averaged ozone distribution of the upper atmosphere. J. Atmos. Sci. 37, 2248-2264.

Gille, J. C., P. L. Bailey, and J. M. Russell III, 1980: Temperature and composition measurements from the LRIR and LIMS experiments on Nimbus 6 and 7. Phil. Trans. Roy Soc. London, A296, 205-218.

Hartmann, D. L., 1981: Some aspects of the coupling between radiation, chemistry, and dynamics in the stratosphere. J. Geophys. Res. 86, 9631-9640.

Hartmann, D. L., and R. R. Garcia, 1979: A mechanistic model of ozone transport by planetary waves in the stratosphere. J. Atmos. Sci. 36, 350-364.

Holton, J. R., 1980a: Wave propagation and transport in the middle atmosphere. Phil. Trans. Roy. Soc. London A196, 73-85.

Holton, J. R., 1980b: The dynamics of sudden stratospheric warmings. Annual Review of Earth and Planetary Science, Vol. 8, Annual Reviews, 169-190.

Kawahira, K., 1982: A quasi-one-dimensional model of the ozone transport by planetary waves in the winter stratosphere. J. Meteor. Soc. Japan, 60, 831-848.

Kurzeja, R. J., K. V. Haggard, and W. L. Grose, 1984: Numerical experiments with a general circulation model concerning the distribution of ozone in the stratosphere. J. Atmos. Sci., 41, 2029-2051.

Labitzke, K., 1981: The amplification of height wave 1 in January 1979: A characteristic precondition for the major warming in February. Mon. Wea. Rev. 109, 985-989.

Labitzke, K., 1982: On the interannual variability of the middle stratosphere during the northern winters. J. Japan. Met. Soc. 60, 124-139.

Labitzke, K., and B. Goretzki, 1982: A catalogue of dynamic parameters describing the variability of the middle stratosphere during the northern winters, in Handbook for MAP., Vol. 5, Middle Atmosphere Program, SCOSTEP, University of Illinois, Urbana.

McCormick, M. P., T. J. Pepin, W. P. Chu, T. J. Swissler and L. R. McMaster, 1979: Satellite studies of the stratospheric aerosol. Bull. Amer. Meteor. Soc. 60, 1038-1046.

Nagatani, R. M., and A. J. Miller, 1984: Stratospheric ozone changes during the first year of SBUV observations. J. Geophys. Res. 89, 5191-5198.

NASA, 1979: The stratosphere: Present and future, NASA Ref. Publ. 1049, 432 pp.

Newell, R. E., 1964: Further ozone transport calculations and the spring maximum in ozone amount. Pure Appl. Geophys. 59, 191-206.

Noxon, J. F., E. Marovich and R. B. Norton, 1979: Effect of a major warming upon stratospheric NO_2. J. Geophys. Res. 84, C12, 7883-7888.

Prabhakara, C. P., 1963: Effects of non-photochemical processes on the meridional distribution and total amount of ozone in the atmosphere. Mon. Wea. Rev. 91, 411-431.

Quiroz, R. S., 1979: Tropospheric-stratospheric interaction in the major warming event of January-February 1979. Geophys. Res. Lett. 6, 645-648.

Rood, R. B., and M. R. Schoeberl, 1983a: A mechanistic model of Eulerian, Lagrangian-mean, and Lagrangian ozone transport by steady planetary waves. J. Geophys. Res. 88, 5208-5218.

Rood, R. B. and M. R. Schoeberl, 1983b: Ozone transport by diabatic and planetary wave circulations on a δ-plane. J. Geophys. Res. 88, C13, 8491-8504.

Schoeberl, M. R., 1978: Stratospheric warmings: Observations and theory. Space Phys. 16, 521-538.

Schoeberl, M. R., and D. F. Strobel, 1980: Sudden stratospheric warmings forced by mountains. Geophys. Res. Lett. 7, 149-152.

Syed, M. Q., and A. W. Harrison, 1981: Behavior of stratospheric NO_2 during stratospheric warming of January-February 1979. Atmos. Ocean 19, 216-235.

Wang, Pi-Huan, M. P. McCormick, and W. Chu, 1983: A study on the planetary wave transport of ozone during the late February 1979 stratospheric warming using the SAGE ozone observation and meteorological information. J. Atmos. Sci. 40, 2419-1431.

World Meteorological Organization, The Stratosphere, 1981: Theory and Measurements, Rep. 11, WMO Global Ozone Res. and Monitoring Proj., Geneva, Switzerland.

Wu, Mao-Fou, M. A. Geller, J. G. Olson, A.M. Miller, and R. M. Nagatani, 1985: Computations of transport using Nimbus 7 solar backscatter ultraviolet and NOAA/National Meteorological Center data. J. Geophys. Res. 90, 5745-5755.

TABLE

The Number of Profiles and the Averaged Latitude of SAGE Observations from February 12 - 21, 1981

Date (February)	Number of Profiles	Averaged Latitude (°N)
12	15	49.47
13	14	50.94
14	15	52.05
15	15	52.84
16	15	53.34
17	15	53.55
18	15	53.50
19	15	53.18
20	15	52.59
21	14	51.69

List of Figures

Figure 11 Phase relationship between ozone mixing ratio (solid line), temperature (dashed line), and eddy meridional velocity (solid and dashed line) waves during the middle February 1981 warming (~52°N). Phase increases westward: (a) wavenumber 1, Feburary 13, 1981; (b) wavenumber 2, February 13, 1981; (c) wavenumber 1, February 17, 1981; and (d) wavenumber 2, February 17, 1981.

Figure 12 Time variation of the phase relationship between ozone mixing ratio (solid line), temperature (dashed line), and eddy meridional velocity (solid and dashed line) waves during the middle February 1981 warming (~52°N). Phase increases westward: (a) wavenumber 1, 44 km altitude; (b) wavenumber 1, 26 km; (c) wavenumber 2, 44 km; (d) wavenumber 2, 26 km.

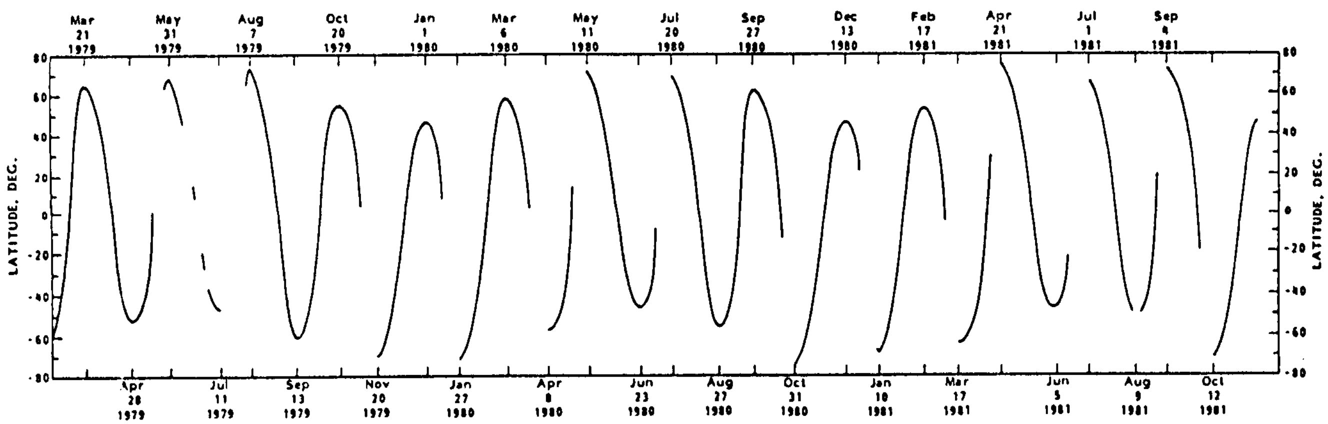

Fig. 1. The latitudinal coverage of SAGE sunset measurements.

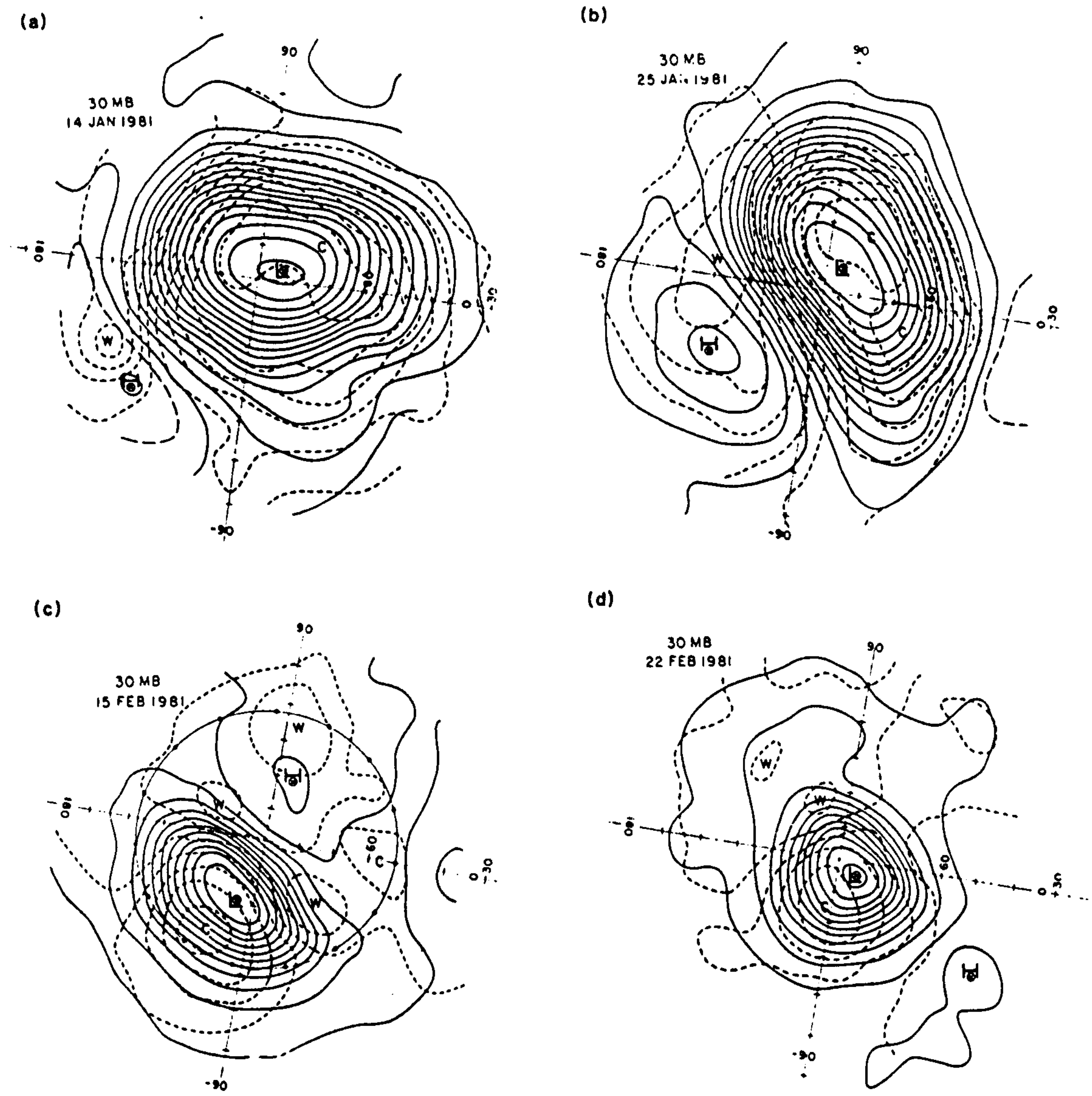

Fig. 2. Constant-pressure upper air maps at 30 mb for (a) January 14, 1981; (b) January 25, 1981; (c) February 15, 1981; and (d) February 22, 1981. —— isobaric altitude lines, ----- isotherms. Solid circles on (c) denote the SAGE measurement locations.

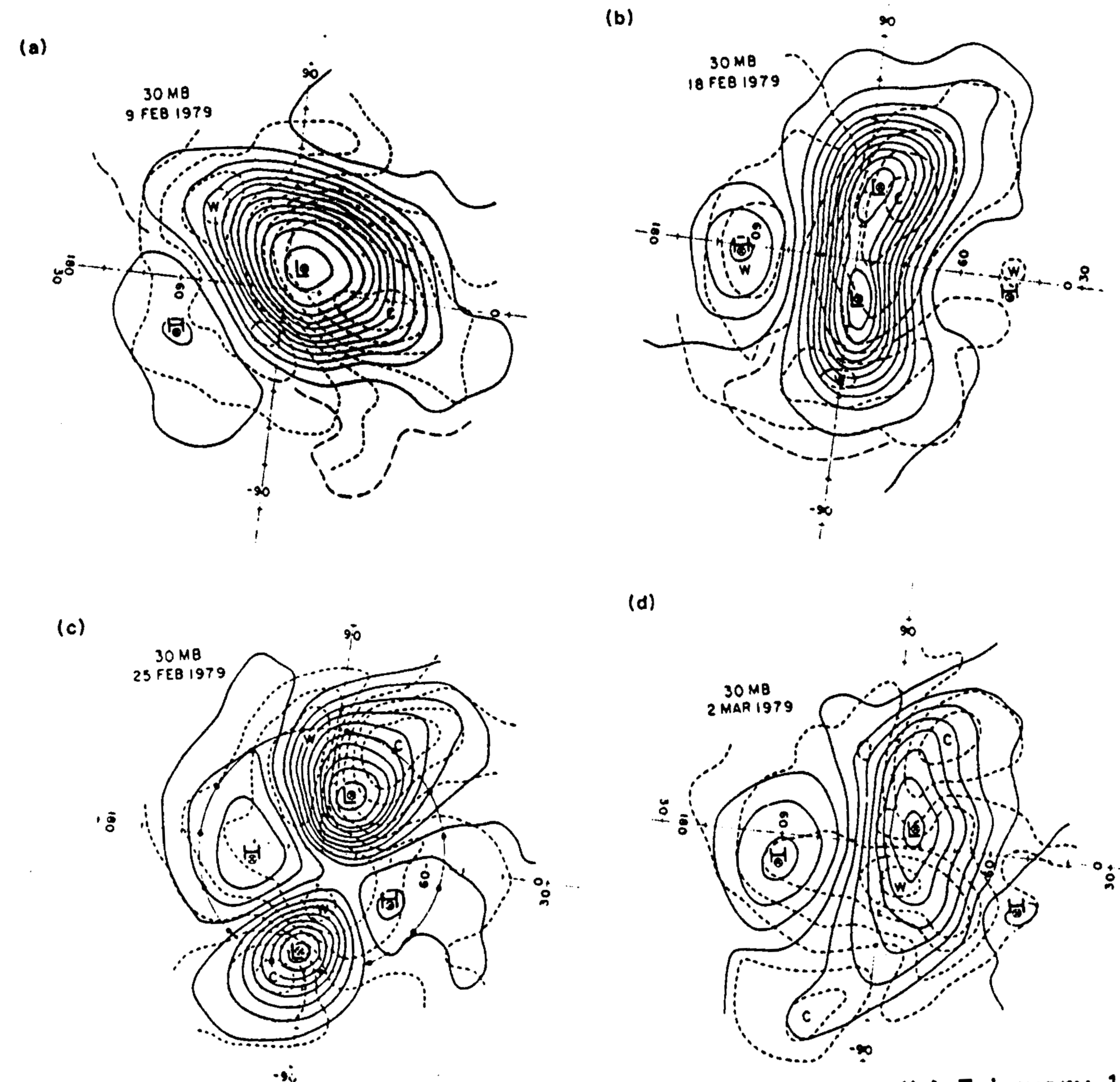

Fig. 3. Constant pressure upper air maps at 30 mb for (a) February 9, 1979; (b) February 18, 1979; (c) February 25, 1979; and (d) March 2, 1979. ——— isobaric altitude lines, ------ isotherms. Solid circles on (c) denote the SAGE measurement locations.

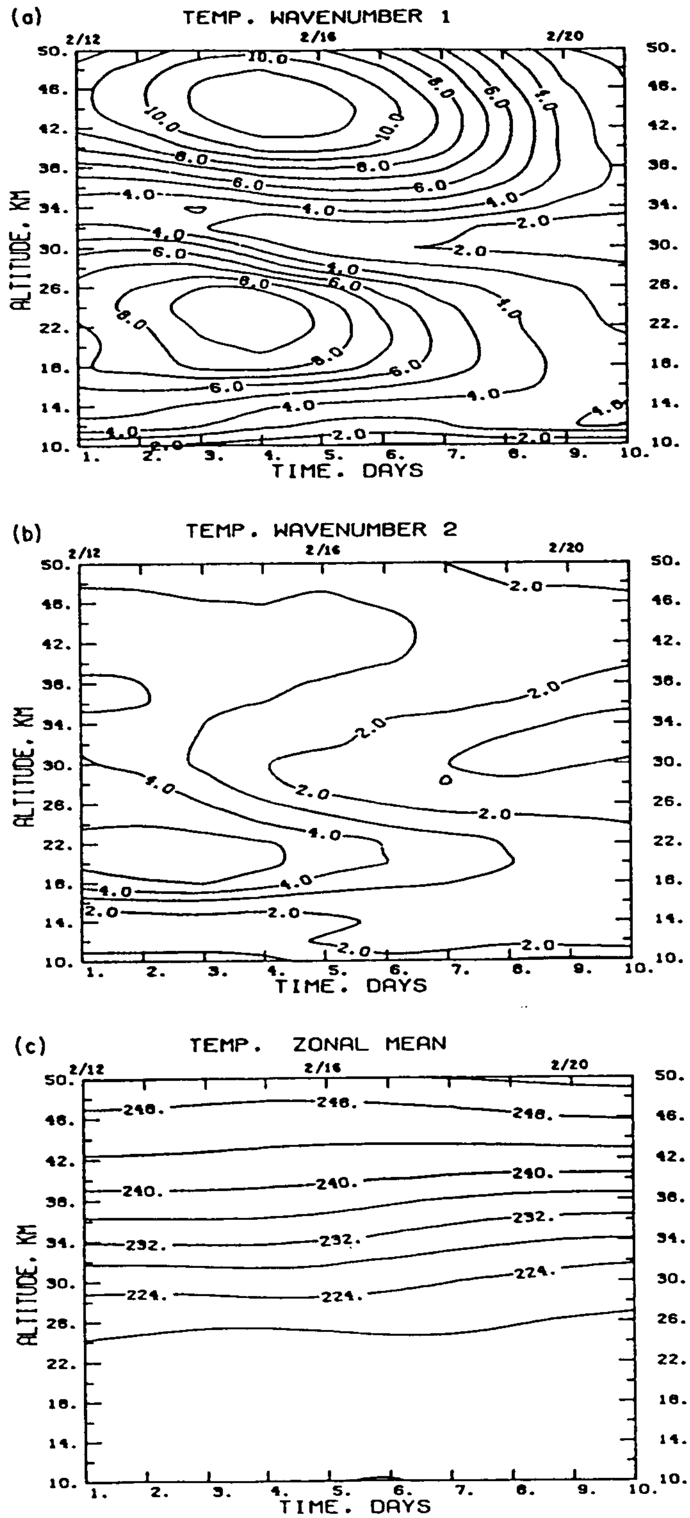

Fig. 4. Evolution of the amplitudes (°C) of the first two temperature waves [(a) and (b), respectively, contour interval 1°C]; and (c) the zonal mean temperature K (contour interval 4°C) during the middle February 1981 warming (~52°N).

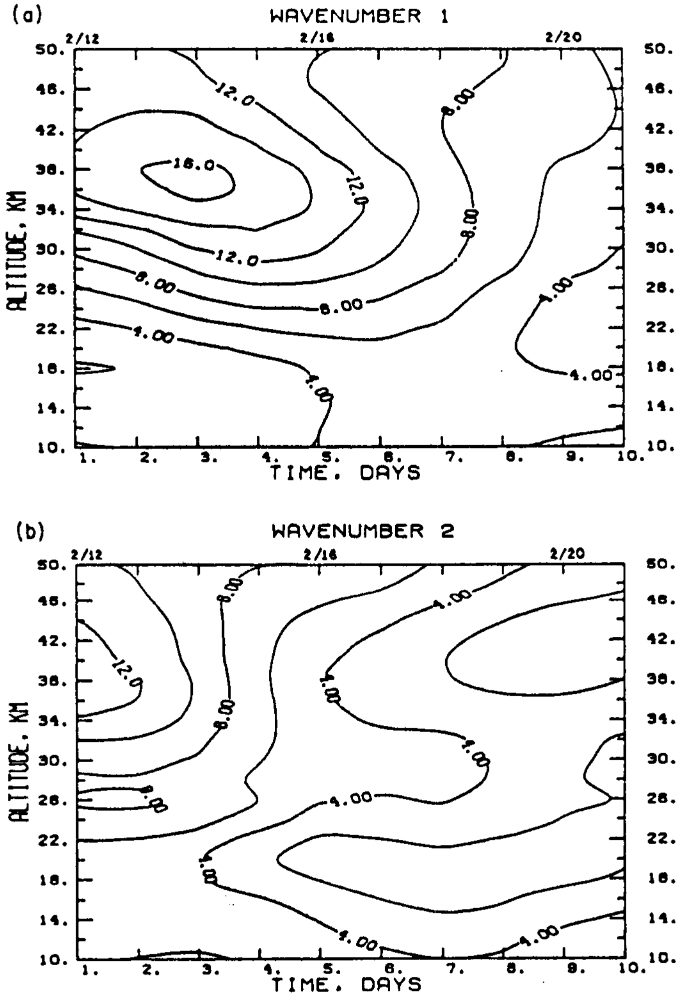

Fig. 5. Evolution of the amplitudes (ms^{-1}) of meridional velocity waves during the middle February 1981 warming (~52°N); (a) wavenumber 1, (b) wavenumber 2; contour interval 4 ms^{-1}.

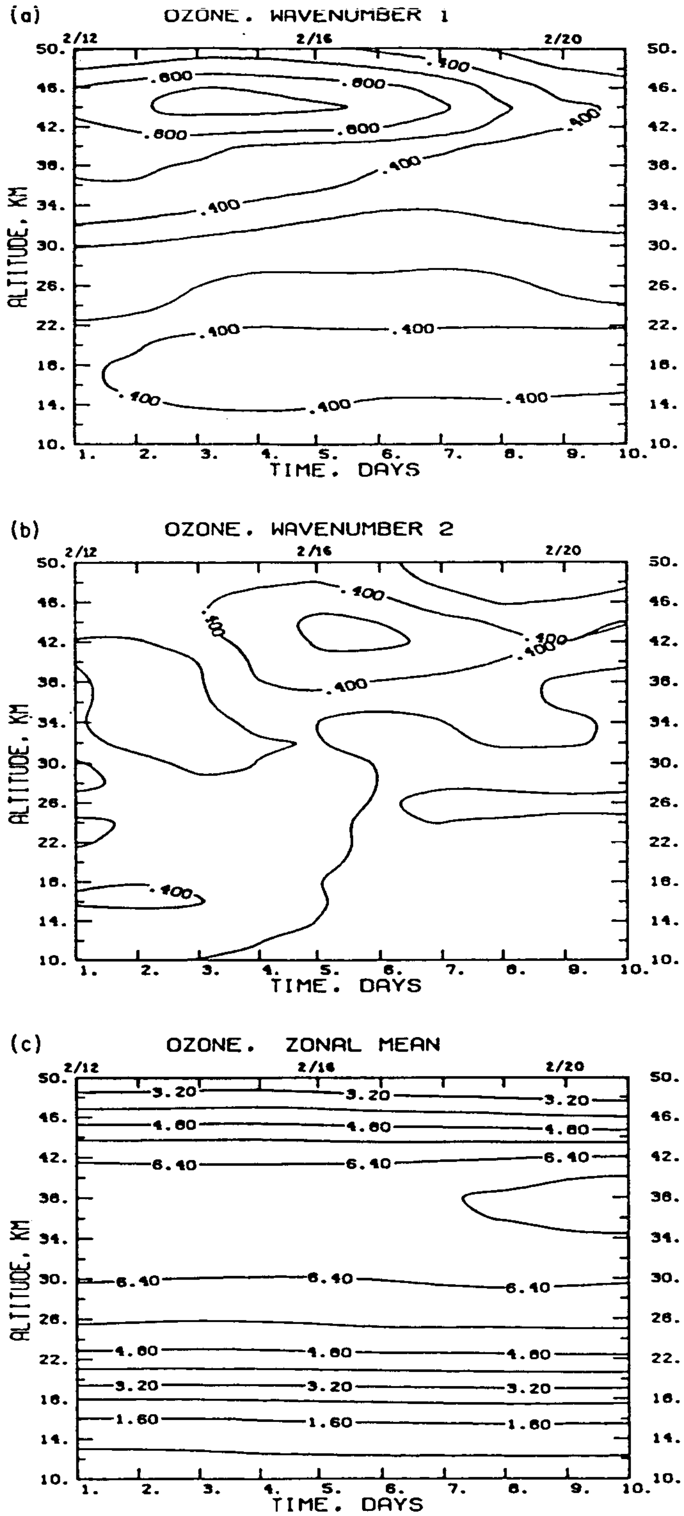

Fig. 6. Evolution of the amplitudes (ppmv) of the first two ozone waves, and the zonal mean ozone during the middle February 1981 warming (~52°N): (a) wavenumber 1; (b) wavenumber 2, contour interval 0.2 ppmv, and (c) zonal mean ozone, contour 0.8 ppmv.

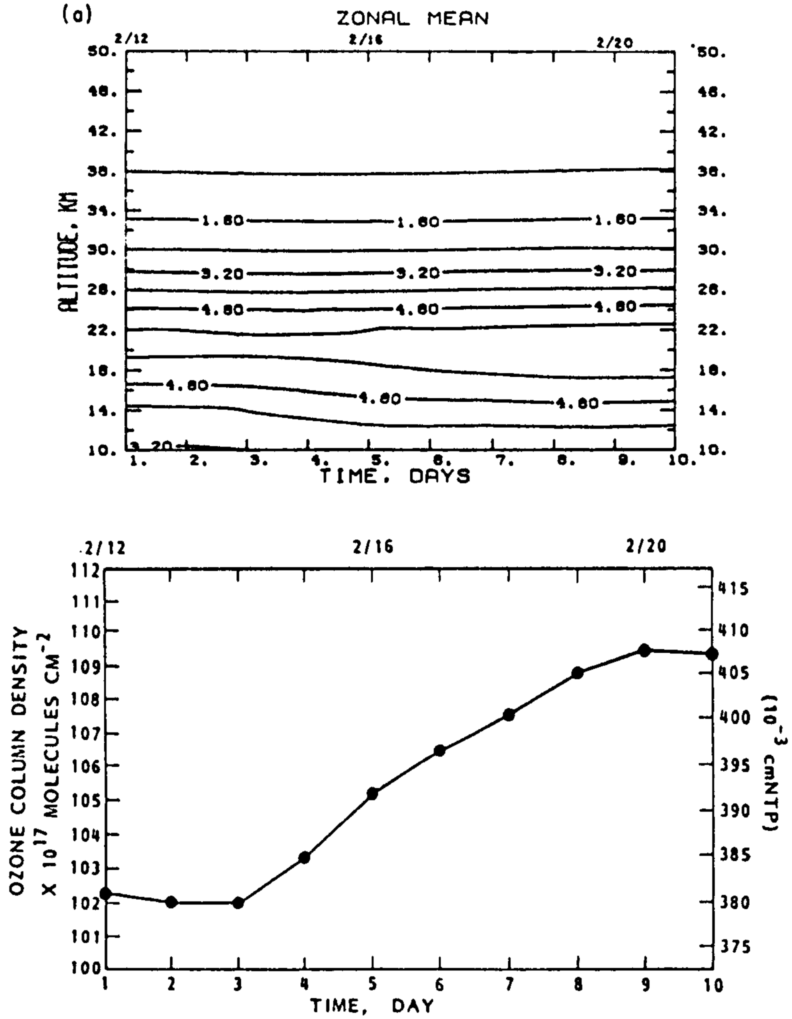

Fig. 7. Evolution of (a) zonal mean ozone number density, contour interval 0.8, scale by 10^{-12} in unit cm^{-3}; and (b) ozone columnar density at altitude 10 km during the middle February 1981 warming (~52°N).

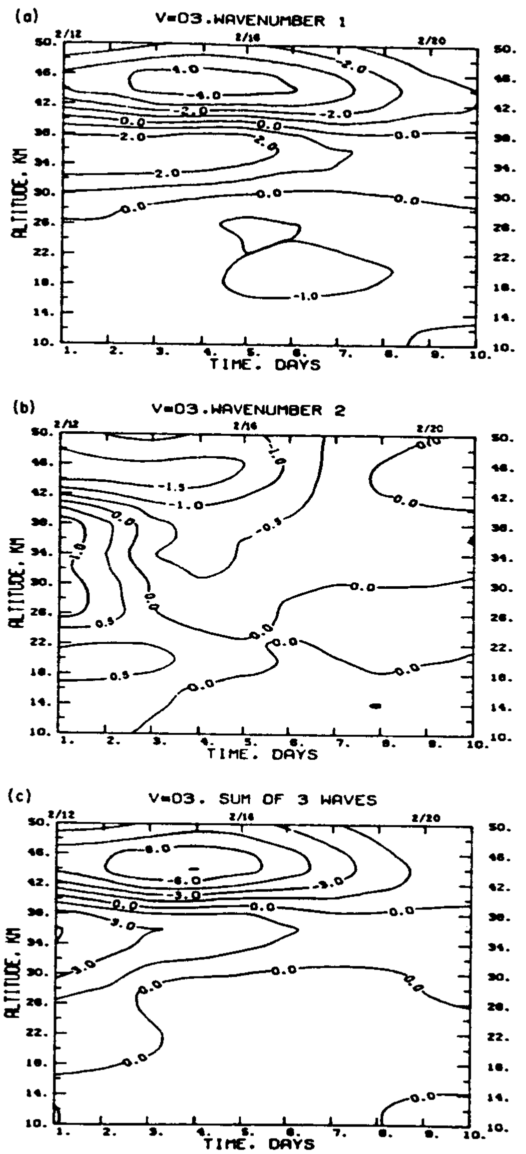

Fig. 8. Time variations of eddy ozone flux (ppm ms^{-1}) due to (a) wavenumber 1, contour interval 1 ppm ms^{-1}, and (b) wavenumber 2, contour interval 0.5 ppm ms^{-1}. The sum of the first three waves is given in (c), contour interval 1.5 ppm ms^{-1}. (+ poleward, - equatorward).

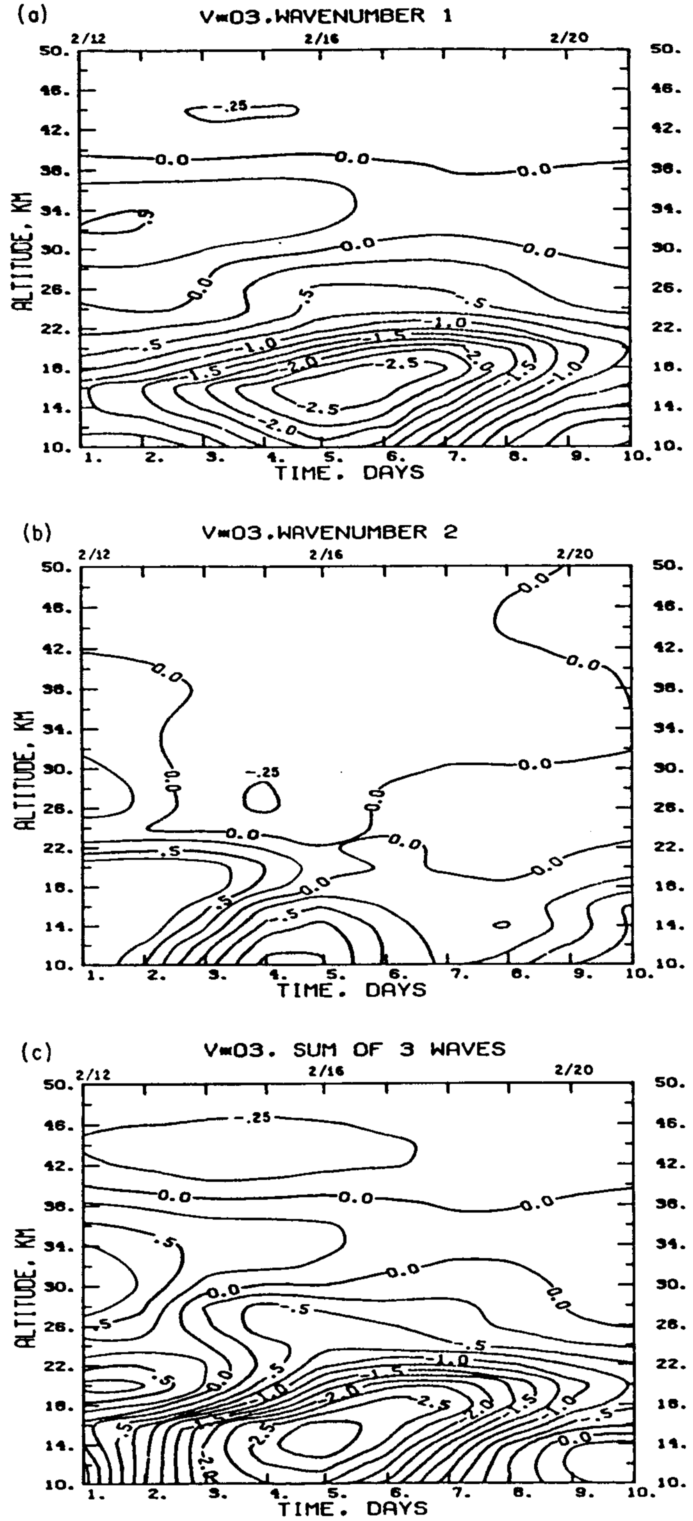

Fig. 9. Time variations of eddy ozone mass transport (molecule $cm^{-3}ms^{-1}$) due to (a) wavenumber 1; and (b) wavenumber 2, contour interval 0.25 molecule $cm^{-3}ms^{-1}$. The sum of the first three waves is given in (c) contour interval 1 molecule $cm^{-3}ms^{-1}$. Scaled by 10^{-12} + poleward, - equatorward).

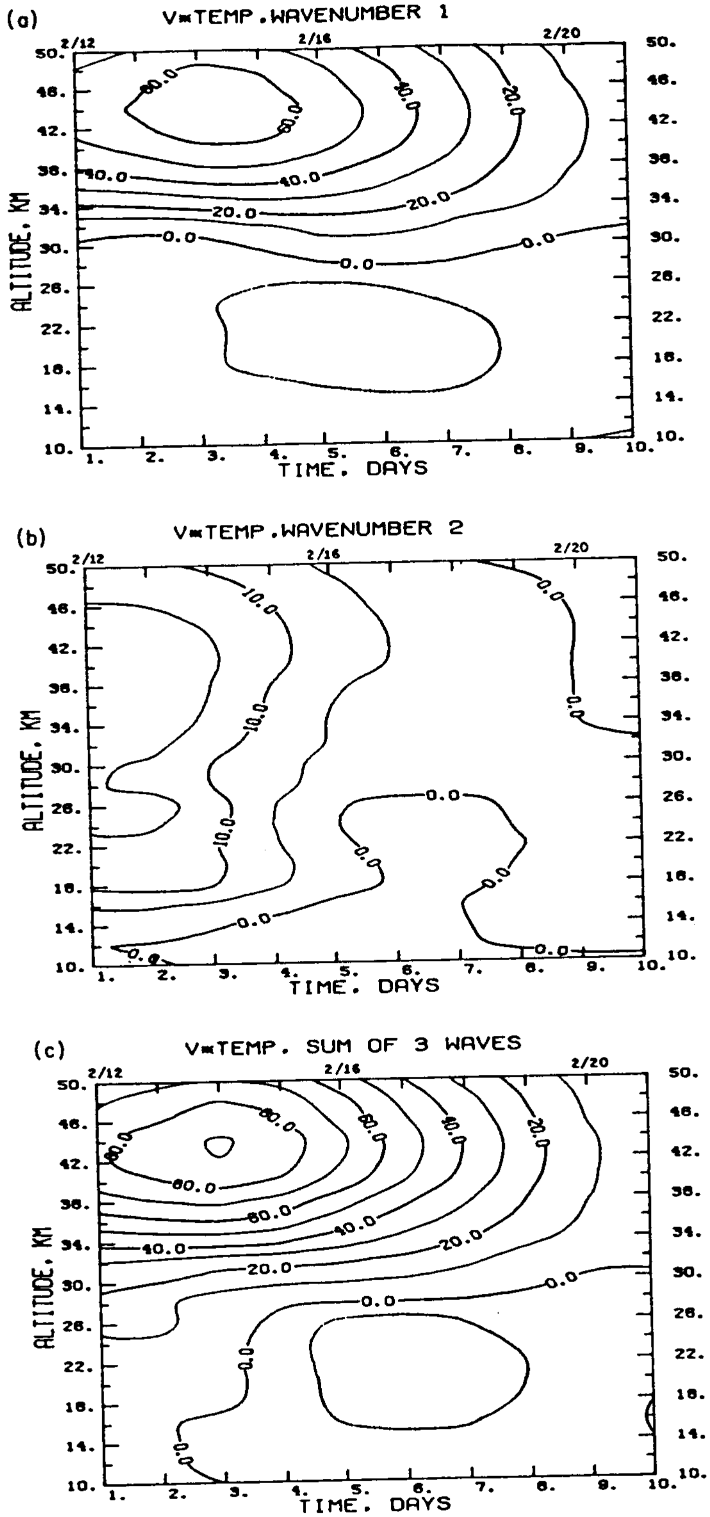

Fig. 10. Time variation of eddy heat flux (k ms^{-1}) due to
(a) wavenumber 1, contour interval 10°C ms^{-1};
(b) wavenumber 2, contour interval 5°C ms^{-1}; and
(c) the sum of the first three waves, contour interval 10°C ms^{-1}. (——— poleward, ----- equatorward)

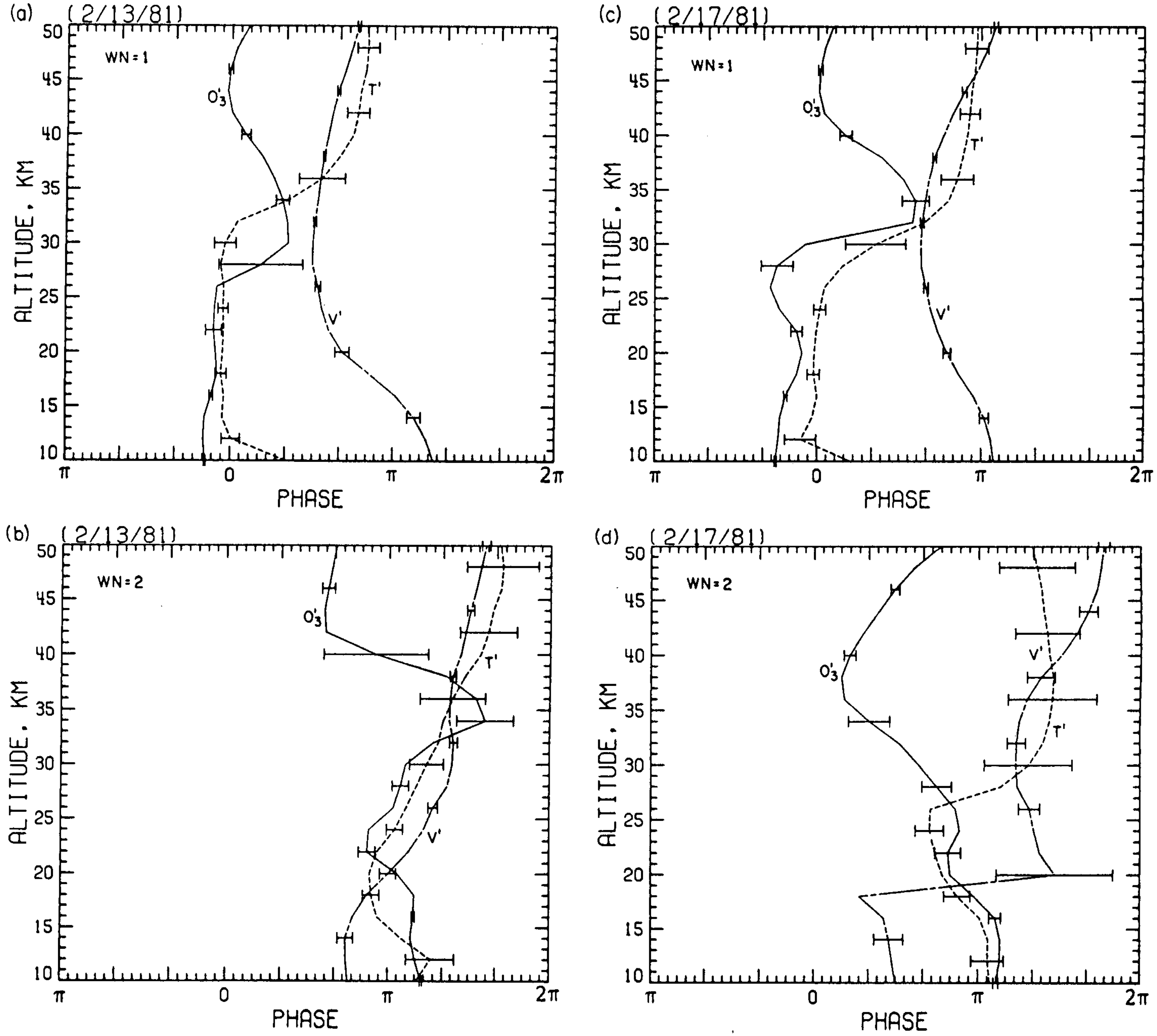

Fig. 11. Phase relationship between ozone mixing ratio (solid line), temperature (dashed line), and eddy meridional velocity (solid and dashed line) waves during the middle February 1981 warming (∿52°N). Phase increases westward: (a) wavenumber 1, February 13, 1981; (b) wavenumber 2, February 13, 1981; (c) wavenumber 1, February 17, 1981; and (d) wavenumber 2, February 17, 1981.

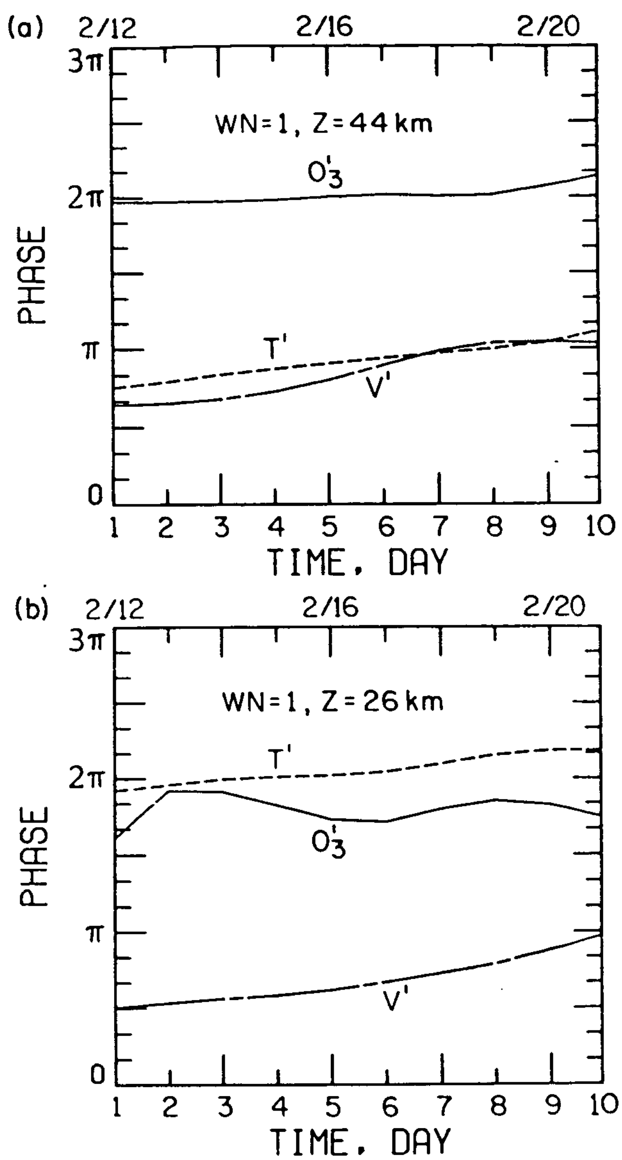

Fig. 12. Time variation of the phase relationship between ozone mixing ratio (solid line), temperature (dashed line), and eddy meridional velocity (solid and dashed line) waves during the middle February 1981 warming (~52°N). Phase increases westward: (a) wavenumber 1, 44 km altitude; (b) wavenumber 1, 26 km; (c) wavenumber 2, 44 km; (d) wavenumber 2, 16 km.